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Associated Risk Factors of Hypertension among Adults in South Africa: Nonparametric Quantile Regression Approach

Anesu Gelfand Kuhudzai*

Statistical and Data Science Consultant, University of Johannesburg, Statistical Consultation Services, South Africa

***Address for Correspondence:** Anesu Gelfand Kuhudzai, Statistical and Data Science Consultant, University of Johannesburg, Statistical Consultation Services, South Africa, Tel: +27-787-689-666; ORCID ID: orcid.org/0000-0003-2867-6865; E-mail: gelfand9@yahoo.com

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ABSTRACT

This paper presents the application of nonparametric quantile regression approach to quantile regression in order to investigate the associated risk factors of hypertension among adults in South Africa. To estimate the partially linear quantile models, the pivotal method of inference based on the orthogonal polynomial basis with five knots at the (0.1, 0.25, 0.5, 0.75, 0.95) quantiles were considered. The factors found to be associated with both Systolic Blood Pressure (SBP) and Diastolic Blood Pressure (DBP) across all quantiles were age, Body Mass Index (BMI) and gender. Race, highest education, smoking, alcohol consumption and health status were significantly associated with both SBP and DBP for part of the quantiles. Suggesting that these are risk factors associated with a higher likelihood of developing essential hypertension in South Africa.

Keywords: Nonparametric quantile regression; Hypertension; Systolic blood pressure; Diastolic blood pressure; South Africa

INTRODUCTION

Globally, hypertension is becoming a public health issue leading to a high risk for death and disability [1]. Hypertension accounts for approximately 9.4 million deaths globally every year [2]. A recent study by [3] revealed that the prevalence of hypertension and associated cardiovascular diseases in sub-Saharan Africa is increasing at an alarming rate.

In Sub-Saharan Africa, South Africa is one of the countries experiencing an exponential increase in raised blood pressure attributable to both non-modifiable and modifiable risk factors [3,4]. Despite the high prevalence rates of hypertension in South Africa, very few large studies on hypertension in South Africa are available.

To curb hypertension in South Africa with right set of interventions, the government, policy makers and ordinary people may need to understand the complete effect of different determinants of high blood pressure. In such a scenario, quantile regression has emerged as a useful tool to estimate effects of predictors at different points of the distribution of the dependent variable [5]. By conducting inference along the full distribution of Systolic Blood Pressure (SBP) and Diastolic Blood Pressure (DBP), it is possible to examine how blood pressure risk factors affects individuals most at risk for hypertension.

On their recommendations for future work highlighted that nonparametric approach to quantile regression will be a useful contribution in the field of conditional quantile estimation [6]. Hence, the main objective of this paper is to utilise nonparametric quantile regression in order to explore the impact of blood pressure risk factors on different quantiles of blood pressure`s distribution. "Nonparametric quantile regression relaxes the usual assumption of linearity and enables exploration of data more flexibly, uncovering structure in the data that might otherwise be missed by classical quantile regression" [7].

MATERIALS AND METHODS

This section presents the theoretical models, the data, variables and data analysis techniques applied in this paper.

Nonparametric quantile regression

Nonparametric quantile regression has emerged as another worthwhile approach to quantile regression, in order to avoid restrictive parametric assumption. Nonparametric quantile regression methods developed by [8] are meant to estimate and make inference on conditional quantile models.

Let Y be a dependent variable of interest, and X is a vector of predictor variables or observable covariates. Suppose the covariate vector $R_G(t)$ is partitioned as $X=(W,V)$, where $t\in[75,225]$ is the main covariate and V is the set of other covariates playing the role of control variables, then the τ -quantile of Y conditional on $X=x$ can be modelled using the following partially linear quantile model

$$Q_{Y|X}(\tau\mid x)=g(\tau,w)+v'\gamma(\tau),\quad \tau\in[0,1] \tag{1}$$

The nonparametric series Quantile Regression (QR) approximation is given in (2) [9]:

$$Q_{Y|X}(\tau\mid x)\approx Z(x)'\beta(\tau),\ \beta(\tau)=\left(\alpha(\tau)',\gamma(\tau)'\right)',\ Z(x)=\left(Z(w)',v'\right)' \tag{2}$$

where the unknown function $g(\tau,w)$ is approximated by a linear combination of series terms $Z(w)'\alpha(\tau)$.

The vector $Z(w)$ includes transformations of w that have good approximation properties such as B-splines, trigonometric terms, powers or indicators. The function $\tau\mapsto\beta(\tau)$ contains the quantile-specific coefficients of the approximation, where $\beta(\tau)$ is defined as the coefficient of the quantile regression of Y on $Z(X)$ at the quantile τ .

The coefficient vector $\beta(\tau)$ is estimated by using the quantile regression estimator [10].

Let $\{(Y_i,X_i):1\le i\le n\}$ be a random sample from (Y,X) and let $\hat{\beta}(\tau)$ be the QR estimator of $\beta(\tau)$ which is given by

$$\hat{\beta}(\tau)\in\arg\min_{\beta\in\mathbb{R}^m}\sum_{i=1}^{n}\rho\tau\left(Y_i-Z(X_i)'\beta\right),\quad \tau\in\tau\subseteq(0,1) \tag{3}$$

where $\rho_\tau(z)=(\tau-1\{z<0\})z$ is the check function, τ is a compact set and $m=\dim\beta(\tau)$.

When performing inference in this setting, there is a challenge that m should increase with the sample size in order to reduce approximation error. As a result, Belloni A, et al. [8] solved this challenge by deriving two couplings or strong approximations (pivotal process and a Gaussian process) of dimension m that are uniformly close to $\tau\mapsto\sqrt{n}\left(\hat{\beta}(\tau)-\beta(\tau)\right)$. In order to estimate the distribution of these coupling processes that can be used to make inference on linear functionals of the conditional quantile function the following methods are provided, conditionally pivotal process, gradient bootstrap process, Gaussian process and weighted bootstrap process. Each of these approximations leads to a feasible inference method.

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Regularity conditions

In the nonparametric QR series framework, the entire model can change with n, as a result Belloni A, et al. [8] used a set of sufficient conditions known as condition S to generate data as $n \to \infty$ and $m = m(n) \to \infty$.

Condition S

S.1 The data $D_n = \left\{ \left(Y_i, X_i' \right)', 1 \le i \le n \right\}$ are an $i.i.d.$ sequence of real $(1+d)$ - vectors, and $Z_1 = Z(X_i)$ is a real m - vector for $i = 1, \ldots, n$.

S.2 The conditional density of the response variable $f_{Y|X}(y \mid x)$ is bounded above by $\overline{f}$ and its derivative in y is bounded above by $\overline{f}'$, uniformly in the arguments y and $x \in \chi$ and in n; moreover, $f_{Y|X}\left(Q_{Y|X}(\tau \mid x) \mid x \right)$ is bounded away from zero uniformly for all arguments $u \in U$, $x \in \chi$, and n.

S.3 For every m, the eigenvalues of the Gram matrix $\sum_m = E[ZZ']$ are bounded from above and away from zero, uniformly in n.

S.4 The norm of the series terms obeys $\max_{i \le n} \| Z_i \| \le \zeta(m,d,n) := \zeta_m$.

S.5 The approximation error term $R(X,U)$ is such that $\sup_{x \in \chi, u \in U} | R(x,u) | \underset{\sim}{<} m^{-k}$.

Pivotal inference method

The pivotal analytical method is based on the pivotal coupling process.The pivotal method is defined in [8] as follows:

Suppose $\hat{J}_m(u)$ denote the estimator of $J_m(u)$ where

$$\hat{J}_m(u) = \frac{1}{2h_n} E_n \left[1\left\{ | Y_i - Z_i' \hat{\beta}(u) | \le h_n \right\} . Z_i Z_i' \right] \tag{4}$$

with bandwidth h_n obeying $h_n = o(1)$ and $h_n \sqrt{m} \log^{3/2} n = o(1)$.

Under Condition S, $m^{-k+1/2} \log^{3/2} n = o(1)$, and $\zeta_m^2 m^2 \log^4 n = o(nh_n)$, the feasible pivotal process $\hat{J}_m^{-1}(.) U_n^*(.)$ correctly approximates a copy $J_m^{-1}(.) U_n^*(.)$ of the pivotal process defined in the following Theorem:

$$\hat{J}_m^{-1}(u) U_n^*(u) = J_m^{-1}(u) U_n^*(u) + r_n(u) \tag{5}$$

where

$$U_n^*(u) := \frac{1}{\sqrt{n}} \sum_{i=1}^{n} Z_i \left(u - 1\left\{ U_i^* \le u \right\} \right) \tag{6}$$

$U_1^*, \ldots, U_n^*$ are $Z_1, \ldots, Z_n$, $i.i.d.$ Uniform (0,1), independently distributed of and

$$\sup_{u \in U} \| r_n(u) \| \le_P \sqrt{\frac{\zeta_m^2 m^2 \log^2 n}{nh_n}} + m^{-k+1/2} \sqrt{\log n} + h_n \sqrt{m \log n} = o(1/\log n) \tag{7}$$

Data analysis

To illustrate nonparametric quantile regression inference with an empirical application, wave 4 secondary data obtained in year 2014-2015 from the South African National Income Dynamics Study database was utilised. Respondents aged 18 and above sampled across South Africa's nine provinces were included (n = 18.205).The study variables are Systolic Blood Pressure (SBP) and Diastolic Blood Pressure (DBP) as the response variables; the predictors are age, Body Mass Index (BMI), gender, race, highest education, exercises, smoking, alcohol consumption, depression and health status. SBP, DBP and the risk factors considered in the study were assessed by using the National Income Dynamics Study Wave 4 (2014/2015) Adult Questionnaire.

The R package "quantreg.nonpar" developed by Lipsitz M, et al. [9] will be used to perform uniform nonparametric estimation and inference on linear functionals of the systolic blood pressure and diastolic blood pressure conditional quantile functions. The partially linear quantile models shall use the empirical specification presented in equation (1).

Where Y = diastolic blood pressure or systolic blood pressure.

W = is the key covariate.

V = is a vector of control variables.

To estimate the partially linear quantile models, the pivotal method of inference based on the orthogonal polynomial basis with five knots at the (0.1, 0.25, 0.5, 0.75, 0.95) quantiles were considered. The empirical results are reported in tables 1-4.

RESULTS AND DISCUSSION

This section presents the empirical results of the study. Also, interpretation of the results is given in this section.

Table 1 shows the breakdown of the sample by gender, race, age and highest education. It can be seen that 7.556 (41.5%) of the respondents were males and 10.649 (58.5%) were females. Most of the participants were African and they were 15.040 (82.6%) and the least number of participants were Asian/Indian and they were 164 (0.9%). Concerning, the age distribution, 7.504 (41.2%) were between 18-29 years, followed by the 50 years and above age group who were 4.268 (23.4%). The least number of participants by age were 2.630 (14.4%) and they were aged between 40 to 49 years.

In terms of highest education attained, the no schooling were

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693 (3.8%), Grade R to 11 were 12 236 (67.2%), Grade 12 were 5 217 (28.7%) and the remaining 59 (0.3%) had a certificate, diploma or degree.

Table 2 presents the profile of the respondents according to their lifestyle characteristics. It is apparent from table 4 that very few respondents 2.414 (13.3%) do exercise three or more times a week. Majority of respondents 13.967 (76.7%) indicated that they do not exercise. A total of 3.750 (20.6%) participants do smoke whilst 14.455 (79.4%) did not smoke.

The study findings illustrate that 12.538 (68.9%) respondents never drank alcohol whilst only 182 (1%) drank alcohol between 5 to 7 days a week. Respondents were asked to indicate the number of times in a week they are likely to suffer from depression. 9.960 (54.7%) respondents revealed that they rarely suffer from depression and only 472 (2.6%) indicated that they are likely to be affected by depression between 5 to 7 days a week.

The study also considered health status, debt status and wealth status as possible risk factors of raised blood pressure. It can be seen from the results in table 4 that 12.035 (66.1%) of the study participants do suffer from 1 or more health conditions whilst 6.170 (33.9%) suffer from no health conditions. Regarding debt status, it is shown that 12.609 (69.3%) respondents have no debt whereas 5.596 (30.7%) do have some debt. Last but not least, 3.683 (20.2%) of the total participants pointed out that they do not own any asset or gadget whilst 14.522 (79.8%) revealed that they do own an asset or gadget.

It is evident in table 4 that, 2.761 (15.2%) of the total respondents had high SBP (more than 140 mmHg) and 3.530 (19.4%) participants had abnormal DBP (more than 90 mmHg). Last but not least, 4.114 (22.6%) study participants were overweight (25-29.9 kg/m^2) and 5.222 (28.7%) were obese, thus 30 kg/m^2 and above.

Table 1: Demographic characteristics.

Characteristic	Category	*n*	Percentage
Gender	Male	7.556	41.5%
	Female	10.649	58.5%
Race	African	15.040	82.6%
	Colored	2.603	14.3%
	Asian/Indian	164	0.9%
	White	398	2.2%
Age	18-29 years	7.504	41.2%
	30-39 years	3.803	20.9%
	40-49 years	2.630	14.4%
	50 and above years	4.268	23.4%
Highest Education	No Schooling	693	3.8%
	Grade R to 11	12.236	67.2%
	Grade 12	5.217	28.7%
	Certificate/Diploma/Degree	59	0.3%

Table 2: Lifestyle characteristics.

		n	Percentage
Exercises	Never/Less than once a week	13.967	76.7%
	Once or Twice a week	1.824	10.0%
	Three or more times a week	2.414	13.3%
Smoking	Yes	3.750	20.6%
	No	14.455	79.4%
Alcohol Consumption	Never drank or no longer drink alcohol	12.538	68.9%
	Drink very rarely or Less than once a week	3.768	20.7%
	Drink between 3 to 4 days a week	1.717	9.4%
	Drink between 5 to 7 days a week	182	1.0%
Depression	Rarely or none of the time (Less than 1 day)	9.960	54.7%
	Some or Little of the time (1-2 days)	5.737	31.5%
	Occasionally or a moderate amount of time (3-4 days)	2.036	11.2%
	All of the time (5-7 days)	472	2.6%
Health Status	Suffering from no condition	6.170	33.9%
	Suffering from 1 or more conditions	12.035	66.1%
Debt Status	No Debt	12.609	69.3%
	Have Debt	5.596	30.7%
Wealth Status	No asset/gadget	3.683	20.2%
	Own asset/gadget	14.522	79.8%
Systolic Blood Pressure	Normal (Less than 120)	10.295	56.6%
	Pre-Hypertension (120-139)	5.149	28.3%
	High Blood Pressure Stage 1 (140-159)	1.830	10.1%
	High Blood Pressure Stage 2 (160 or higher)	588	3.2%
	Hypertensive Crisis (Higher than 180)	343	1.9%
Diastolic Blood Pressure	Normal (Less than 80)	10.143	55.7%
	Pre-Hypertension (80-89)	4.532	24.9%
	High Blood Pressure Stage 1 (90-99)	2.201	12.1%
	High Blood Pressure Stage 2 (100 or higher)	891	4.9%
	Hypertensive Crisis (Higher than 110)	438	2.4%
Body Mass Index	Underweight (< 18.50)	1.177	6.5%
	Healthy (18.50-24.99)	7.692	42.3%
	Overweight (25.00-29.99)	4.114	22.6%
	Obese (30.00-34.99)	2.823	15.5%
	Very Obese (35.00-39.99)	1.514	8.3%
	Morbidly Obese (40.00)	885	4.9%

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Table 3 shows the point estimates and the uniform confidence intervals in parentheses for each SBP`s risk factor. According to Belloni, et al. [9], point estimates denote the average derivative of the conditional quantile function with respect to the key covariate of interest. It is apparent from this table that age and BMI indicate statistically significant positive effects on all quantiles of the SBP distribution as revealed by the 95% uniform confidence intervals which does not include zero. These findings suggest that the proportion of South African adults suffering from high blood pressure is likely to rise due to an increase in age and BMI. These results are consistent with those of [11], that the risk of suffering from hypertension increases as one gets older possibly because of the effects of aging which include loss of blood vessel flexibility and increased sensitivity to salt and other dietary factors. With regard to BMI, the study results confirms with other research that BMI is significantly associated with hypertension [12] and individuals who are overweight and obese are at high risk of developing high blood pressure [13].

Race had a positive significant influence across all quantiles except the 95th quantile implying that the hypertension prevalence is likely to decrease among black Africans than other ethnic groups. This finding is in contrast to that one of [11], that black Africans are more likely to develop hypertension than Whites and Asians/Indians due to a combination of genetic, dietary and lifestyle factors.

Gender was found to be negatively associated with SBP across all quantiles. This finding indicates that raised SBP is likely to increase more in males than females, confirming previous research that suggest that prevalence of hypertension is higher in males than females until after menopause [14]. According to Stibich [11], more females are likely to develop hypertension after menopause because of the decline in the protective effect of oestrogen.

Highest level of education attained was also negatively associated with SBP across all quantiles except the 10th quantile, suggesting that participants with low levels of education are more prone to hypertension as compared to individuals with tertiary education. This finding in this study mirror those of the previous studies that have observed that less educated subjects have higher prevalence of hypertension than medium-high subjects [15]. Smoking had a negatively significant effect only on the 75th quantile of SBP suggesting that respondents who smoke are more liable to suffer from high SBP than who do not smoke a finding that is in line with previous research that smoking increases blood pressure acutely and increases the risk of renovascular, malignant, and masked hypertension [16].

Another interesting finding of this study was that health status was found to negatively affect the lower quantiles (10th and 25th) as well as positively influence the upper quantiles (95th) of SBP suggesting some mixed results. Alcohol consumption, depression and exercises did not present statistically significant relations with SBP across all quantiles (i.e. $\tau \in \{0.10, 0.25, 0.50, 0.75, 0.95\}$). It seems possible that these results are due to very few participants who indicated that they consume alcohol regularly i.e. 3 days or more per week (10.4%), suffer from depression occasionally or all the time (13.8%) and exercises regularly i.e. 3 or more times a week (13.3%) respectively.

Table 3: Uniform nonparametric quantile regression estimates and 95% confidence intervals for SBP`s risk factors.

τ	Q(0.10)	Q(0.25)	Q(0.50)	Q(0.75)	Q(0.95)
Age	0.29 (0.17,0.41)	0.33(0.23,0.44)	0.51(0.40,0.61)	0.70(0.58,0.83)	1.12(0.86,1.37)
BMI	0.59(0.52,0.67)	0.61(0.54,0.68)	0.59(0.51,0.67)	0.59(0.49,0.69)	0.64(0.43,0.85)
Gender	-8.97(-10.06,-7.89)	-9.63(-10.62,-8.64)	-10.72(-11.70,-9.75)	-10.65(-11.81,-9.48)	-10.35(-12.82,-7.88)
Race	1.58(0.79,2.36)	2.27(1.60,2.94)	2.53(1.73,3.34)	2.07(0.96,3.12)	1.21(-1.86,4.27)
Highest Education	-0.50(-1.39,0.39)	-1.31(-2.13,-0.49)	-2.39(-3.47-1.32)	-3.07(-4.30,-1.84)	-5.30(-7.71,-2.89)
Exercises	-0.87(-2.50,0.76)	-0.29(-1.75,1.17)	-0.66(-2.18,0.85)	-1.53(-3.36,0.30)	0.69(-3.03,4.41)
Smoking	-0.14(-1.51,1.22)	-0.40(-1.61,0.82)	-0.67(-1.92,0.57)	-2.13(-3.68,-0.57)	-2.68(-5.58,0.22)
Alcohol Consumption	0.05(-0.43,0.53)	0.20(-0.23,0.64)	0.27(-0.17,0.71)	0.40(-0.16,0.97)	0.67(-0.53,1.87)
Depression	-0.47(-1.18,0.24)	-0.46(-1.11,0.18)	-0.38(-1.07,0.31)	-0.29(-1.16,0.59)	0.17(-1.68,2.01)
Health Status	-0.96(-1.79,-0.13)	-0.83(-1.60,-0.05)	-0.21(-1,01,0.59)	-0.07(-1.07,0.92)	2.12(0.03,4.20)

Table 4: Uniform nonparametric quantile regression estimates and 95% confidence intervals for DBP`s risk factors.

τ	Q(0.10)	Q(0.25)	Q(0.50)	Q(0.75)	Q(0.95)
Age	0.23(0.13,0.33)	0.27(0.18,0.36)	0.31(0.22,0.39)	0.38(0.29,0.48)	0.52(0.32,0.71)
BMI	0.51(0.44,0.57)	0.52(0.46,0.58)	0.51(0.46,.0.57)	0.52(0.45,0.59)	0.56(0.44,0.68)
Gender	-2.22(-3.05,-1.39)	-2.37(-3.03,-1.70)	-2.84(-3.51,-2.18)	-2.44(-3.21,-1.67)	-1.96(-3.45,-0.46)
Race	0.71(0.13,1.28)	0.89(0.43,1.34)	0.56(0.04,1.07)	0.22(-0.44,0.88)	0.59(-1.78,2.97)
Highest Education	-0.13(-0.90,0.63)	-0.34(-0.97,0.28)	-0.44(-1.12,0.23)	-0.72(-1.46,-0.02)	-1.15(-3.12,0.83)
Exercises	-0.44(-1.75,0.86)	-0.48(-1.67,0.70)	0.02(-1.16,1.21)	-0.41(-1.68,0.87)	-0.58(-3.19,2.04)
Smoking	-0.37(-1.40,0.65)	-0.77(-1.65,0.11)	-0.97(-1.84,-0.09)	-1.95(-3.02,-0.89)	-2.62(-4.58,-0.67)
Alcohol Consumption	0.26(-0.17,0.68)	0.39(0.04,0.75)	0.49(0.12,0.85)	0.83(0.41,1.24)	0.97(0.13,1.81)
Depression	0.17(-0.41,0.74)	-0.11(-0.60,0.38)	0.02(-0.49,0.53)	-0.05(-0.66,0.56)	-0.43(-1.63,0.78)
Health Status	-0.04(-0.74,0.66)	-0.12(-0.74,0.49)	0.2(-0.38,0.81)	0.50(-0.21,1.21)	2.02(0.63,3.40)

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Table 4 presents the regression coefficients and the uniform confidence intervals in parentheses for DBP`s risk factors. The results reveals some similarities and differences in the role of predictors at different conditional distribution points of DBP as compared to SBP. Similarly to SBP, age, BMI and gender presented statistically significant relations with DBP across all quantiles whilst exercises and depression did not influence DBP across all quantiles. Also, health status was found to present a statistically significant effect on the 95th quantile of DBP`s distribution.

In contrast to the results found on SBP, highest education had an influence on the 75th quantile of DBP only. With regard to smoking, it was found to have a negative effect on the middle and upper quantiles of DBP. Race presented statistically significant positive relations with DBP`s median and lower quantiles.

Surprisingly, alcohol consumption was positively associated with DBP across all quantiles except the 10th quantile, implying that participants who do not drink alcohol are less liable to suffer from hypertension than those who drink regularly. These results match those observed in earlier epidemiological, preclinical and clinical studies which have revealed an association between high alcohol consumption and hypertension [17].

CONCLUSION

In an attempt to complement the results achieved using the Bayesian approach presented in a previous study by the same author [18], a nonparametric quantile regression approach was conducted as another approach of quantile regression meant to relax the parametric distribution assumption. To estimate the partially linear quantile models, the pivotal method of inference based on the orthogonal polynomial basis with five knots at the (0.1, 0.25, 0.5, 0.75, 0.95) quantiles was considered. The R package "quantreg.nonpar" was used to estimate and make inference on SBP`s and DBP`s conditional quantile functions.

The factors found to be associated with both SBP and DBP across all quantiles were age, BMI and gender. Race, highest education, smoking, alcohol consumption and health status were significantly associated with both SBP and DBP for part of the quantiles. Suggesting that these risk factors are associated with a higher likelihood of developing essential hypertension.

Comparing Bayesian Quantile regression estimates [18], against the nonparametric quantile regression results presented in this paper, diverse marginal effects (in magnitudes) of each risk factor on different SBP and DBP quantiles are evident. However, the range of the nonparametric quantile regression uniform confidence intervals are wider than the Bayesian credible intervals implying that Bayesian interval estimation produce results with a better precision.

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ETHICAL CONSIDERATION

The South African National Income Dynamics Survey was conducted after ethical approval was granted by the University of Cape Town, Faculty of Commerce Ethics Committee. Informed consent was also obtained from each study participant.

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